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# Experimental implementation of distributed flocking algorithm for multiple robotic fish

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ABSTRACT

This paper presents the experimental implementation of a flocking algorithm for multiple robotic fish governed by extended second-order unicycles. Combing consensus protocols with attraction/repulsion functions, a flocking algorithm is proposed to make the agents asymptotically converge to swim with consistent velocities and approach the equilibrium distances to their neighbors. The LaSalle–Krasovskii invariance principle is applied to verify the stability of the system. Besides numerical simulations, platform simulations involving robotic fish kinematic constraint and control mechanism are shown. An experiment with three robotic fish is implemented to illustrate the effectiveness of the proposed flocking algorithm in the presence of external disturbance and boundary collision.



## 1. Introduction

The coordination control of multiple robotic fish has attracted increasing attention from scholars around the world, owing to its potential applications to kinds of underwater tasks such as environmental survey, search and rescue, and ocean exploration. In recent years, rapid advances in sensing and communication technologies have led to the possibility of the realization of the mature coordination control strategies of multi-agent systems on modern vehicles.

Flocking is one of the most significant research fields in coordination control of multi-agent systems, and flocking phenomena can be widely observed among fish in nature. In the colony, each agent depends on local sensing and simple rules to coordinate its behavior for the sake of keeping a common velocity while moving as a compact group. The classical flocking model was proposed by Reynolds (1987), consisting of collision avoidance, velocity matching, and flocking centering. Since then, many variants of these three properties have been suggested, and relative control algorithms have also been proposed (Dimarogonas, Loizou, Kyriakopoulos, & Zavlanos, 2006; Jadbabaie, Lin, & Morse, 2003; Leonard & Fiorelli, 2001; Luo, Liu, Guan, & Li, 2012; Olfati-Saber, 2006; Sabattini, Secchi, & Fantuzzi, 2011; Su, Chen, Wang, & Lin, 2010; Tanner, Jadbabaie, & Pappas, 2007).

Therein, some authors have investigated the applications of these flocking algorithms to mobile vehicles. For example, Savkin and Teimoori (2009) proposed a decentralized method for global flocking formation of multiple unicycles with velocity constraints, but they only involved the heading control of agents. Supposing that the interaction network is a complete graph, Falconi, Sabattini, Secchi, Fantuzzi, and Melchiorri (2011) described a formation control strategy using attractive/repulsive functions to construct formation and avoid collision for holonomic kinematic models. Regmi, Sandoval, Byrne, Tanner, and Abdallah (2005) gave an experimental implementation of flocking algorithms in wheeled mobile robots, but did not take the problem of finite communication into consideration. Su, Wang, and Chen (2010) presented one solution to deal with the finite communication problem by adding constraint conditions to the potential function. Gu and Wang (2009) investigated a leader–follower flocking system consisting of a network of first-order unicycles with varying forward speeds and varying rotational speeds, and successfully applied the flocking algorithm to a group of real robots called "wifibots".

However, new challenges are brought for multiple robotic fish due to their unique kinematic characteristics and special swimming environments. Firstly, although three-dimensional swimming capabilities of robotic fish have been studied, the implementation of coordination algorithms on underwater vehicles is still restricted to surface communication or tethered underwater vehicles because of the limited underwater communication and localization technology (Klein, Bettale, Triplett, & Morgansen, 2008). Thus, the robotic fish under consideration only swim in the water surface. Secondly, the flocking task realized by multiple robotic fish should be a dynamic one, as it is hard to keep the robotic fish stay in one place. Hence, the robotic fish should be simplified into a second-order kinematic model. Thirdly, due to the uncertainty and the complexity of underwater environments,

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it is required that the control algorithm should be able to resist uncertain disturbances to some extent.

In this paper, a distributed flocking algorithm is presented for the robotic fish system governed by the extended second-order unicycle model. By using the nearest neighbor interaction rules (Jadbabaie et al., 2003), agents communicate with each other under switching topologies with undirected information flow. Suppose that the initial interaction network is an undirected connected graph. The stability of the closed-loop system is proved by applying the LaSalle–Krasovskii invariance principle. Besides velocity matching and collision avoidance, flocking centering and connectivity preservation are also realized. The results of a numerical simulation are shown to verify the effectiveness of the proposed approach. Further efforts are made to illustrate the theoretical results on another simulation platform considering kinematic constraints and control mechanisms of the robotic fish. Finally, the desired flocking phenomenon can be observed among three robotic fish swimming in a pool.

The rest of this paper is organized as follows. The flocking problem of multiple robotic fish is formulated in Section 2. Section 3 presents a distributed control algorithm to solve the flocking problem. In Section 4, the experimental implementation of the proposed flocking algorithm is shown by three robotic fish. Finally, the conclusions are drawn in Section 5.

## 2. Problem formulation

Consider a group of $N$ radio-controlled, multi-link, and free-swimming biomimetic robotic fish swimming in the water surface. Each robotic fish propels itself by undulating its flexible body and caudal fin. The motion of the robotic fish can be simply decomposed into forward motion and rotational motion. Zhang, Wang, Yu, and Tan (2007) simplified the robotic fish into a point model with kinematic characteristics of a first-order unicycle. The main propulsive force of the robotic fish comes from the latter part of its body. As shown in Fig. 1, the geometrical center and the mass center of the robotic fish do not coincide. Suppose that $\mathbb{N}$ is the set of positive integers and $\mathbb{R}$ the set of real numbers. Then, the swimming robotic fish $i$ $(i=1,\ldots,N)$ can be further drawn by an extended second-order unicycle model

$$\begin{aligned}
\dot{x}_i(t) &= \upsilon_i(t)\cos\theta_i(t) - \omega_i(t) l_i \sin\theta_i(t) \\
\dot{y}_i(t) &= \upsilon_i(t)\sin\theta_i(t) + \omega_i(t) l_i \cos\theta_i(t) \\
\dot{\theta}_i(t) &= \omega_i(t) \\
\dot{\upsilon}_i(t) &= a_i(t) + \delta_i^1(t) \\
\dot{\omega}_i(t) &= b_i(t)/l_i + \delta_i^2(t)/l_i
\end{aligned} \tag{1}$$

where $p_i(t) = [x_i(t), y_i(t)]^T \in \mathbb{R}^2$ denotes the position vector of robotic fish $i$ at time $t$, $\theta_i(t) \in \mathbb{R}$ the heading angle of robotic fish $i$ at time $t$, $\upsilon_i(t) \in \mathbb{R}$ the forward speed of robotic fish $i$ at time $t$, $\omega_i(t) \in \mathbb{R}$ the rotational speed of robotic fish $i$ at time $t$, $l_i$ the distance between the geometrical center $C_i$ and the mass center $M_i$ of robotic fish $i$, $\vartheta_i(t) = \omega_i(t) l_i \in \mathbb{R}$ the tangential speed of robotic fish $i$ at time $t$, $a_i(t) \in \mathbb{R}$ the forward acceleration of robotic fish $i$ at time $t$, $b_i(t) \in \mathbb{R}$ the rotational acceleration of robotic fish $i$ at time $t$, $\delta_i^1(t) \in \mathbb{R}$ the uncertain term added to the forward acceleration of robotic fish $i$ at time $t$, $\delta_i^2(t) \in \mathbb{R}$ the uncertain term added to the rotational acceleration of robotic fish $i$ at time $t$, and $\delta_i(t) = [\delta_i^1(t), \delta_i^2(t)]^T \in \mathbb{R}^2$ the uncertain intrinsic dynamics and the external disturbance (such as water-wave disturbance and other uncertain terms) of robotic fish $i$ at time $t$. Here, $\theta_i(t) \in [0, 2\pi)$ is positive for anticlockwise rotation. The individual differences are not considered into the theoretical analysis. Thus, it should be noted that $l_i = l_d$, $i = 1, 2, \ldots, N$, where $l_d$ is a positive constant.

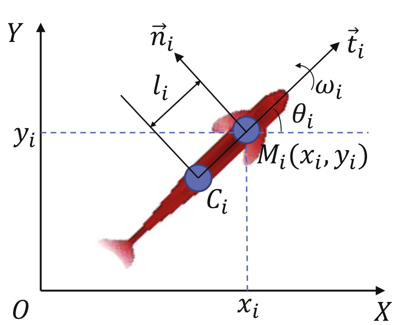


**Fig. 1.** The kinematic model of robotic fish.

Each robotic fish has a limited interaction capability, and it can only interact with its neighbors. Let $N_i(t)$ denote the neighbor set of robotic fish $i$ at time $t$. The neighbor set of robotic fish $i$ at initial time $t_0 = 0$ is defined as $N_i(0) = \{j \mid \|p_i(0) - p_j(0)\| < D,\ j = 1, \ldots, N,\ j \neq i\}$, where $\|\bullet\|$ is the Euclidean norm, and $D > 0$ is the interaction radius. Each robotic fish is able to obtain the state information of its neighbors via the interaction network. Then the interaction network of the robotic fish system can be represented by an undirected graph $G(t)$ with node set $\nu = \{1, 2, \ldots, N\}$ and edge set $\varepsilon(t) \subset \nu \times \nu$. Here, $\nu$ is finite and nonempty. For $i, j \in \nu$, if $i$ and $j$ are neighbors at time $t$, one has $(i, j) \in \varepsilon(t)$. An undirected path is a sequence of unordered edges of the form $(i_1, i_2), (i_2, i_3), \ldots$, where $i_k \in \nu$. An undirected graph is connected if any two nodes can be connected by an undirected path.

In order to clarify the neighbor relationship, graph $G(t)$'s adjacency matrix $W(t)$ and Laplacian matrix $L(t)$ are respectively introduced. $W(t) = [w_{ij}(t)]_{N\times N}$ is defined as

$$w_{ij}(t) = \begin{cases} 1, & (j, i) \in \varepsilon(t) \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

and $L(t) = [l_{ij}(t)]_{N\times N}$ is defined as

$$l_{ij}(t) = \begin{cases} -w_{ij}(t), & i \neq j \\ \sum\limits_{k=1, k\neq i}^{N} w_{ik}(t), & i = j \end{cases} \tag{3}$$

For an undirected graph, the Laplacian matrix is symmetric and positive semi-definite.

Given that the initial interaction network $G(0)$ is an undirected connected graph. In order to preserve the connectivity of the interaction network $G(t)$, the hysteresis adding new edges to the network is introduced (Zavlanos, Jadbabaie, & Pappas, 2007), such that (1) if $(i, j) \in \varepsilon(t^-)$ and $\|p_i(t) - p_j(t)\| < D$, then $(i, j) \in \varepsilon(t)$, for $t > 0$; (2) if $(i, j) \notin \varepsilon(t^-)$ and $\|p_i(t) - p_j(t)\| < D - \varsigma$, where $0 < \varsigma < D$, then $(i, j) \in \varepsilon(t)$, for $t > 0$. Suppose that the interaction network $G(t)$ switches at $t_r$, $r = 1, 2, \ldots$. $G(t)$, is a fixed graph in each nonempty, bounded, and contiguous time-interval $[t_{r-1}, t_r)$.

It is not easy to draw the characteristics of uncertain disturbances in the underwater environment. In order to simplify the problem, the special characteristics of underwater environment are not considered into many theoretical analysis on the coordination control of multiple underwater vehicles (Shao, Wang, & Yu, 2008; Yu, Wang, Shao, & Tan, 2007; Zhang et al., 2007). However, in most cases, the influences of the water-wave and other uncertain terms on the underwater vehicles cannot be ignored. In this paper, $\delta_i(t)$ is supposed to satisfy the following constraint conditions:

$$\begin{aligned}
\delta_i^1(t) &= k_1 \sum_{j \in N_i(t)} (1 - 2r_1(t))(\upsilon_i(t) - \upsilon_j(t)) + k_2 r_2(t) l_d \omega_i(t) \\
\delta_i^2(t) &= k_1 \sum_{j \in N_i(t)} (1 - 2r_1(t)) l_d (\omega_i(t) - \omega_j(t)) - k_2 r_2(t) \upsilon_i(t)
\end{aligned} \tag{4}$$

where $k_1 \in [0, 1)$ and $k_2 \in [0, 1)$ are constants, and $r_1(t), r_2(t)$ respectively denote a random number between $[0, 1)$ generated at time $t$.